The Geological Society of America
2009

Aeolian features and processes

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INTRODUCTION

Aeolian processes, involving erosion, transportation, and deposition of sediment by the wind, occur in a variety of environments, including the coastal zone, cold and hot deserts, and agricultural fields. Common features of these environments are a sparse or nonexistent vegetation cover, a supply of fine sediment (clay, silt, and sand), and strong winds. Aeolian processes are responsible for the emission and/or mobilization of dust and the formation of areas of sand dunes. They largely depend on other geologic agents, such as rivers and waves, to supply sediment for transport.

Areas of sand dunes occur in inland and coastal settings, where they often provide a distinctive environment that provides habitats for endemic and rare or threatened species. In both coastal and inland settings, dune migration and sand encroachment may impact neighboring ecosystems and resources, as well as infrastructure.

Transport of fine sediment by wind may cause **dust storms**, events in which visibility is reduced to less than 1 km by blowing dust. Dust storms impact air quality in their immediate vicinity as well as in areas downwind. Deposition of dust may have a significant effect on the composition and nature of soils in arid regions and beyond. Far-traveled dust from distant sources may have a significant effect on soil chemistry and nutrient status (e.g., Farmer, 1993).

Aeolian Processes, Landforms, and Deposits

This section provides a brief introduction to aeolian processes and landforms and their deposits. For more detailed information and an in-depth discussion of the topic, see Lancaster (1995) for desert dunes, and Nordstrom et al. (1990) for coastal dunes. Goudie and Middleton (2006) provide an excellent review of desert dust processes, while Goudie et al. (1999) provide a good short overview of aeolian processes in general.

Transport of Particles by Wind

Movement of particles by the wind takes place by a combination of direct wind shear stress and atmospheric turbulence. There are three modes of sediment transport by wind: **creep** or reptation; **saltation**, and **suspension** (Fig. 1). The mode of transport depends primarily on the ratio between particle settling velocity, and hence particle size, and wind shear stress and turbulence intensity. Very small particles (<20 microns) are transported in suspension (tens of km or greater) and are kept aloft by turbulent eddies in the wind. True suspension occurs when the particle settling velocity is very small compared to the turbulence intensity of the wind. Larger particles (20–70 microns) undergo short-term suspension for distances of tens to hundreds of meters; material of sand size (70–1000 microns) is transported mainly in a series of short hops (saltation), in which the vertical component of wind velocity (turbulence) has a minimal effect on particle trajectories. Material coarser than 500 microns in diameter (coarse sand) is transported on surface by reptation and creep. The modes of transport are interdependent: saltating sand particles eject silt- and

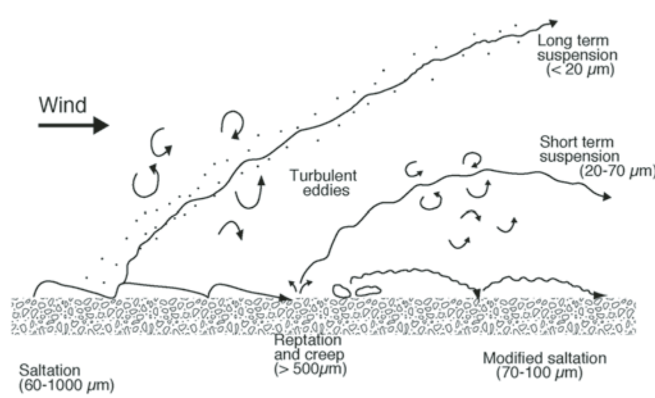

Figure 1. Modes of sediment transport by the wind (after Pye, 1987).

Lancaster, N., 2009, Aeolian features and processes, *in* Young, R., and Norby, L., Geological Monitoring: Boulder, Colorado, Geological Society of America, p. 1–25, doi: 10.1130/2009.monitoring(01). For permission to copy, contact editing@geosociety.org.

clay-sized particles into the wind and impact coarse grains that are rolled along the bed.

Grains begin to move and sediment is entrained by the wind when fluid forces (lift, drag, moment) exceed the effects of the weight of the particle, and any cohesion between adjacent particles as a result of moisture, salts, or soil crusts. The threshold wind speed at which grains begin to move is strongly dependent on particle size (Fig. 2A). For quartz sand, the minimum threshold velocity is associated with fine sand (~100 microns diameter). The mass flux or transport rate of sand has been determined by numerous laboratory wind tunnel and field studies to be proportional to the cube of wind shear velocity above a threshold value (Fig. 2B). For any wind shear velocity, there is a potential rate of sand transport or transport capacity, which is only reached when

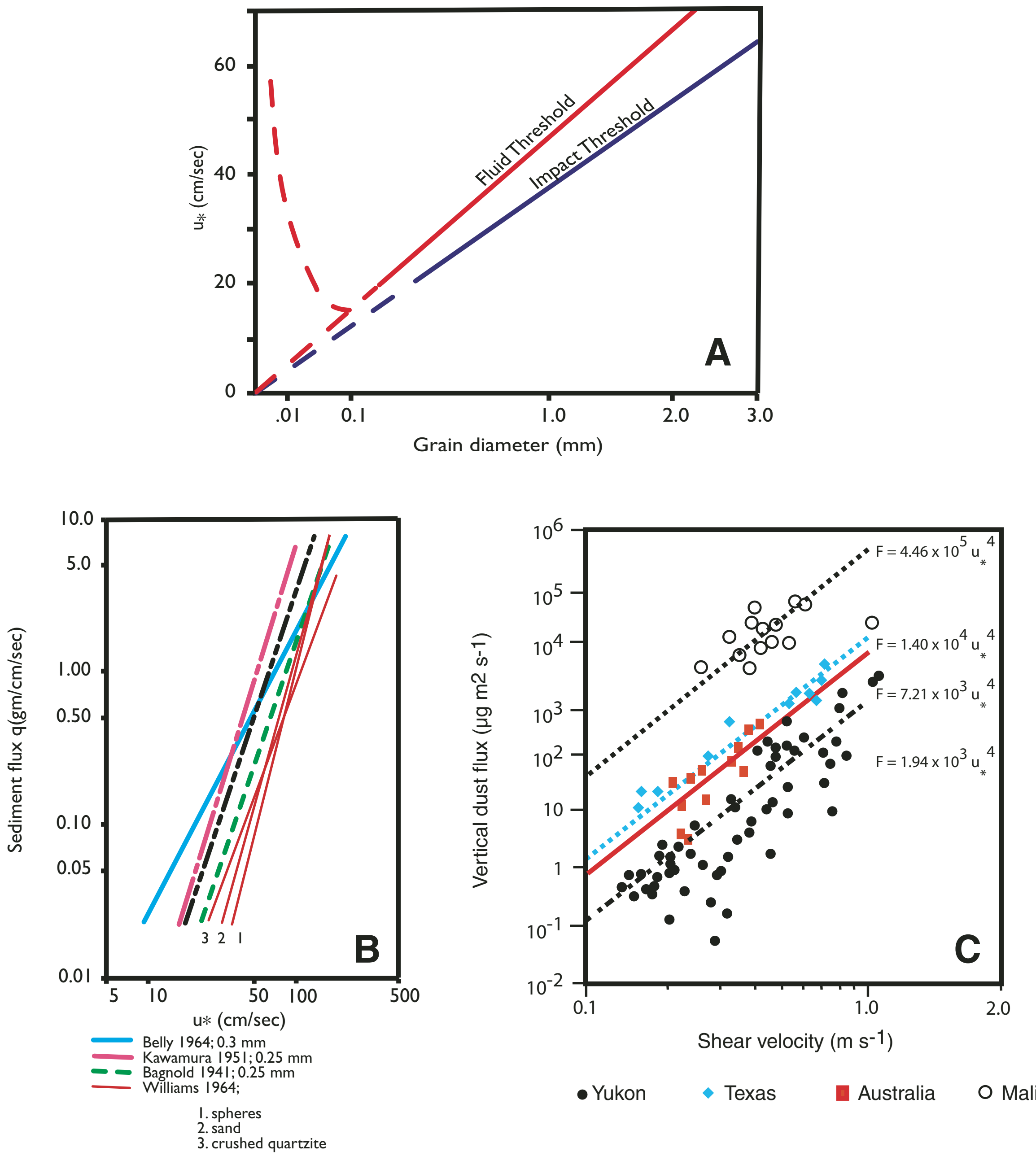

Figure 2. Transport of sediment by the wind: (A) Relation between threshold wind shear velocity and particle size (from (Bagnold, 1941). (B) Mass flux of sand as a function of wind shear velocity (from Lancaster, 1995). Data from laboratory wind tunnel experiments. (C) Relations between horizontal flux of sand-sized particles and vertical flux of dust (from Nickling et al., 1999). Data from field experiments. Figure from Lancaster (2005).

the availability of sediment is unrestricted (e.g., most loose sand surfaces). In these conditions, the wind is saturated with respect to transport capacity.

Very fine grains (silt and clay size) are inherently resistant to entrainment, yet are readily transported by the wind. Recent studies have shown the critical role of impacting sand grains in the mobilization of silt- and clay-size particles and demonstrated the close relations between the horizontal flux of sand-size particles and the vertical flux of fine particles. In these situations, the horizontal mass transport rate is directly related to shear velocity (Fig. 2B), so dust emissions scale to the fourth power of wind shear velocity (Fig. 2C). Where there is a limited supply of particles able to abrade soil clods or playa crusts, dust emissions are limited by the supply of particles rather than the wind shear velocity, and the vertical flux of dust is almost independent of wind shear velocity.

Wind Erosion

Erosion by wind involves two linked processes: **abrasion** (mechanical wearing of coherent materials, including playa crusts and clods created by tillage) and **deflation** (removal of loose material). Considerable attention has been devoted to the processes and rates of wind erosion because of their impact on agriculture, especially in semi-arid regions, and the implications of dust emissions for air quality. Wind erosion abrades crops, removes organic matter, nutrients and fertilizer, and changes soil texture. The products of wind erosion (especially dust particles) impact air quality, atmospheric radiative properties, and human health, causing respiratory illnesses. Rates of wind erosion vary widely and for a given wind shear velocity are dependent on soil or sediment texture and the degree of crusting and cohesion. The highest emission rates for fine-grained sediment are associated with soils of loamy texture, especially those that have been disturbed by vehicular traffic and/or animals.

Aeolian Deposits

Aeolian deposits include sand seas and dune fields, deposits of silt (loess), and fine-grained material that forms a significant component of desert margin and other soils.

Aeolian deposits—silt and clay size. Deposits of wind-transported, silt-sized quartz particles, termed **loess**, cover as much as 10% of Earth's land surface. Loess deposits are widespread in areas of northern China, southern central Asia, central Europe, Argentina, Alaska, and the central United States. Much of the material was thought to be derived from silt particles produced by glacial grinding and supplied to aeolian processes by glacial outwash ("glacial loess"), but other processes, including frost shattering, salt weathering, reduction in size during transport by rivers, and aeolian abrasion are important, especially in the formation of "desert loess."

Silt- and clay-sized material of aeolian origin is also an important component of many desert margin soils. Deposition of silt plays a role in the formation of many stone pavement surfaces in desert regions (desert pavement). These surfaces are characterized by a surface layer of gravel or larger **clasts** (particles) that overlie fine-grained materials. Detailed studies of these surfaces show that the surface layer of gravel rests on a layer of soil-modified dust that may be a meter or more thick and mantles bedrock or materials deposited by other processes (e.g., alluvial sediments). The dust is trapped by the clasts and deposited between them. The fine material is incorporated into the mantle by the shrinking and swelling of clay minerals so that the clasts remain at the surface as they inflate over periods of thousands of years.

Aeolian deposits—sand dunes. Aeolian dunes form part of a hierarchical system of self-organizing bedforms which comprises: (1) wind ripples (spacing 0.1–1 m); (2) individual simple dunes or superimposed dunes on compound and complex dunes (spacing 50–500 m); and (3) compound and complex (mega-) dunes or **draa** (spacing more than 500 m). Dunes occur wherever there is a sufficient supply of sand-sized sediment, winds to transport that sediment, and conditions that promote deposition of the transported sediment. These requirements are satisfied in two main environments: (1) coastal areas with sandy beaches and onshore winds; and (2) desert areas. Most dunes occur in contiguous areas of aeolian deposits called sand seas (>100 km^2) or **dune fields**.

Wind ripples (Fig. 3) typically have a wavelength of 0.05–0.2 m and an amplitude of 0.005–0.010 m. They are ubiquitous on sand surfaces, except those undergoing very rapid erosion or deposition, and form because a flat sand surface over which sand transport by saltation and reptation occurs is dynamically unstable.

Aeolian dunes occur in a self-organized pattern that depends on the wind regime (especially its directional variability) and the supply of sand. Sand dunes occur in four main morphologic types (Fig. 4): **Crescentic** (transverse), **linear**, **star**, and **parabolic**. The simplest dunes form in areas characterized by a narrow

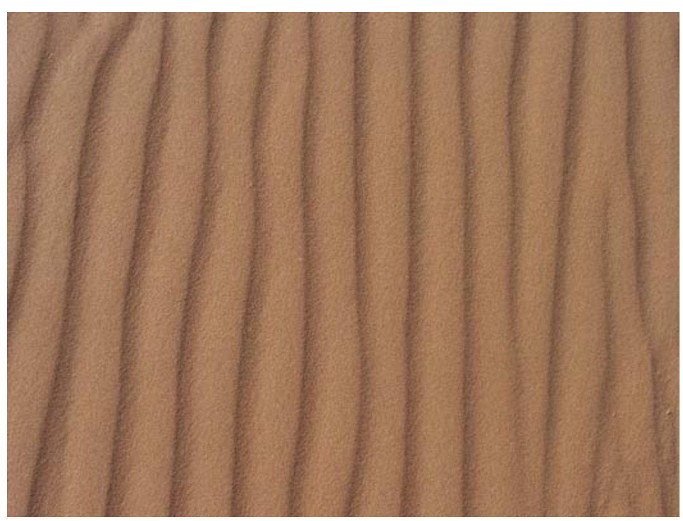

Figure 3. Wind ripples, Gran Desierto, Mexico. Wind direction from left to right.

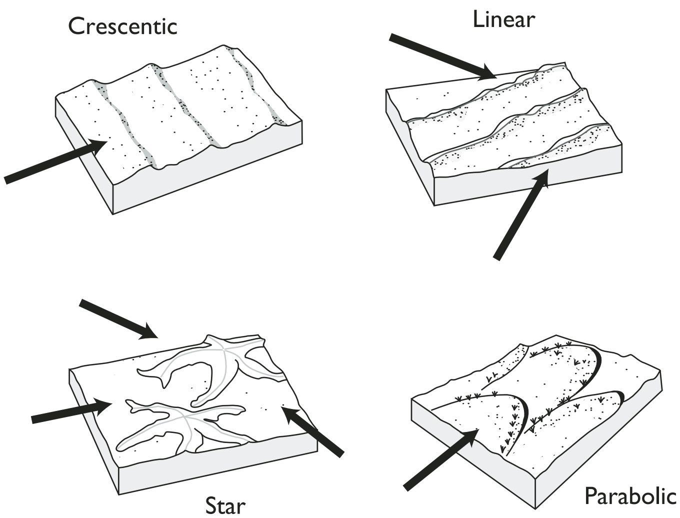

Figure 4. Major dune types (after McKee, 1979b).

range of wind directions. In the absence of vegetation, **crescentic** dunes will be the dominant form. Isolated crescentic dunes or barchans occur in areas of limited sand supply, and coalesce laterally to form crescentic or barchanoid ridges as sand supply increases (Figs. 5A and 5B). **Linear** dunes are characterized by their length (often more than 20 km) sinuous crestline, parallelism, and regular spacing (Figs. 5C and 5D). They form in areas of bimodal or wide unimodal wind regimes. **Star** dunes have a pyramidal shape, with three or four sinuous sharp-crested arms radiating from a central peak and multiple avalanche faces (Fig. 5E). Star dunes occur in multidirectional or complex wind regimes and are the largest dunes in many sand seas, reaching heights of more than 300 m. **Parabolic** dunes (Fig. 5F) are characterized by a U or V shape with a "nose" of active sand and two partly vegetated arms that trail upwind. They are common in many coastal dune fields and semi-arid inland areas, and they often develop from localized blowouts in vegetated sand surfaces. Other important dune types include nebkhas, or hummock dunes, anchored by vegetation (common in many coastal dune fields); lunettes (often composed of sand-sized clay pellets) that form downwind of small playas; and a variety of topographically controlled dunes (climbing and falling dunes, echo dunes).

Relations between dune types and wind regimes indicate that the main control of dune type is the direction of the wind (Fig. 6). Grain size, vegetation cover, and sediment supply play subordinate roles in desert areas. In semi-arid and coastal areas, vegetation cover plays a major role in aeolian dynamics.

STRESSORS AND POSSIBLE CHANGES

The state of an aeolian geomorphic system is controlled by the supply of sediment of a size suitable for transport by the wind; the mobility of the supplied sediment, which is controlled by wind conditions; and the availability of sediment for transport, determined by vegetation cover and soil moisture (Kocurek and Lancaster, 1999). Changes in these external drivers can be the result of climate or human impacts. Climate change and variability affects the mobility of sediment through variations in wind strength; vegetation cover and soil moisture are directly influenced by the amount of precipitation; the supply of sediment may be affected by changes in wave energy, beach sediment budgets, or river discharge. Changes to aeolian systems that can be attributed to the effects of climate variability on annual to decadal time scales include changes in the magnitude and frequency of dust storms (Middleton, 1989), sand transport rates (Lancaster and Helm, 2000), and activation or stabilization of areas of sand dunes (Wolfe, 1997). Such changes are a good indication of the response of a landscape to drought periods. In addition, human impacts may affect vegetation cover by grazing pressure or trampling by animals or people, and increase sediment availability of soils due to disturbance by animals or off-road vehicles. Humans can also directly or indirectly affect sediment supply from rivers or the coastal zone.

VITAL SIGNS

Three main groups of vital signs for aeolian features and processes have been identified. First, rates of sediment movement by the wind give an indication of the magnitude and frequency of aeolian transport events in an area, as well as changes in time and space in response to stressors. Measurements or estimates of rates of sediment transport (sand and/or dust) by the wind provide information on the quantity of sediment transported in this manner and therefore the likely contribution of wind action to erosion and deposition. Second, dune field dynamics provide information on how areas of dunes are responding to external and internal stressors, including disturbance, changes in sediment supply, and climate change and variability. Lastly, dune dynamics provide information on how individual dunes or groups of dunes are responding to stressors.

The level of effort and cost for each monitoring method are summarized in Table 1.

VITAL SIGN 1: FREQUENCY AND MAGNITUDE OF DUST STORMS

The magnitude and frequency of dust storms is an index of rates of wind erosion in the immediate vicinity of a defined location. Reduction of visibility by blowing dust may also indicate an influx of dust from neighboring upwind sources. In addition to the methods described below, some information may also be obtained from the visibility monitoring programs maintained by the Air Resources Division of the National Park Service and its cooperators, available at http://www2.nature.nps.gov/air/monitoring/.

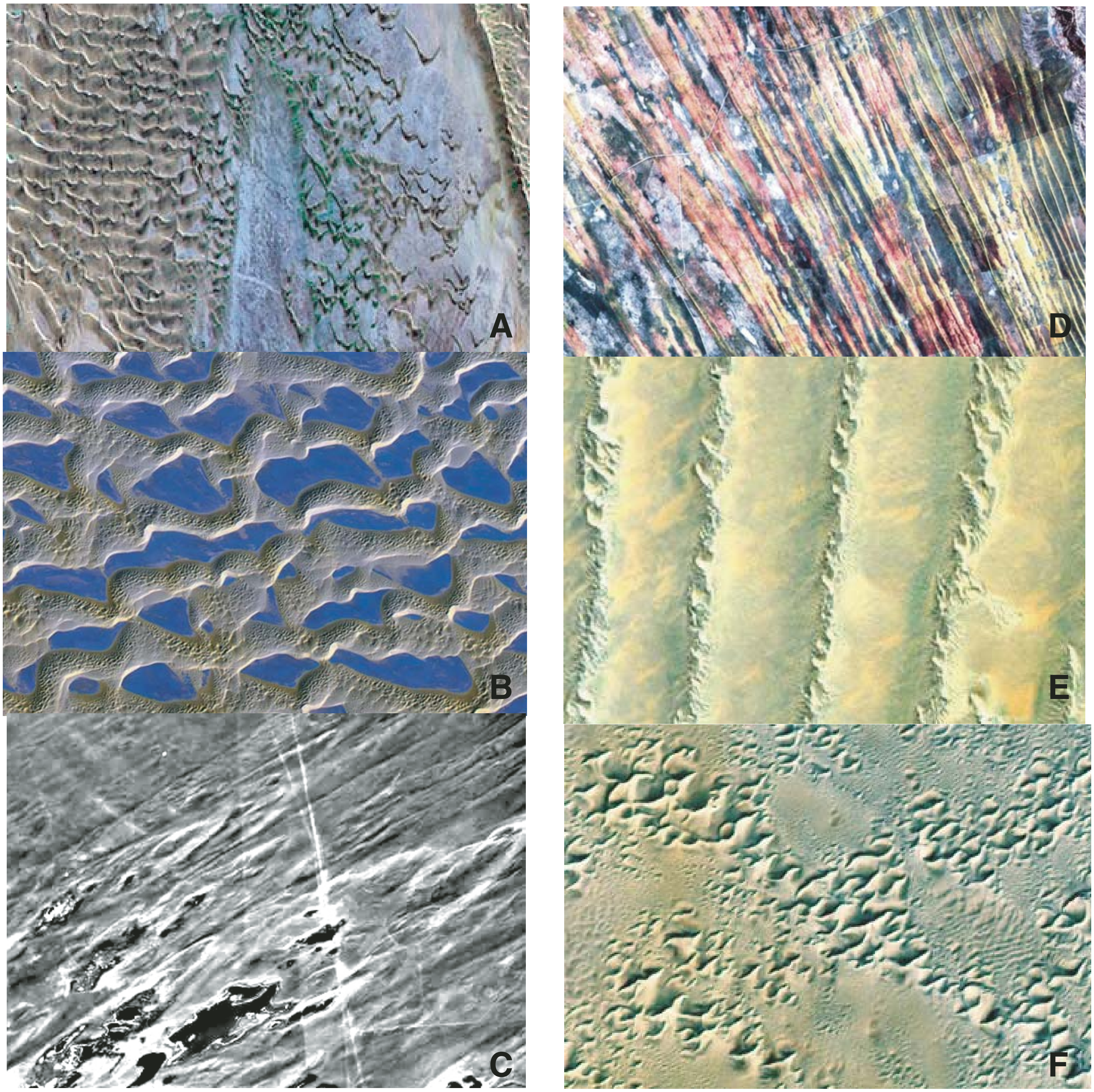

Figure 5. Satellite images and aerial photographs of major dune types: (A) barchans and crescentic dunes, Namib Sand Sea; (B) compound crescentic dunes (Liwa, United Arab Emirates); (C) parabolic dunes, Casper, Wyoming; (D) simple linear dunes (Kalahari Desert); (E) complex linear dunes (Namib Sand Sea); (F) star dunes (Gran Desierto, Mexico). Figure from Lancaster (2005).

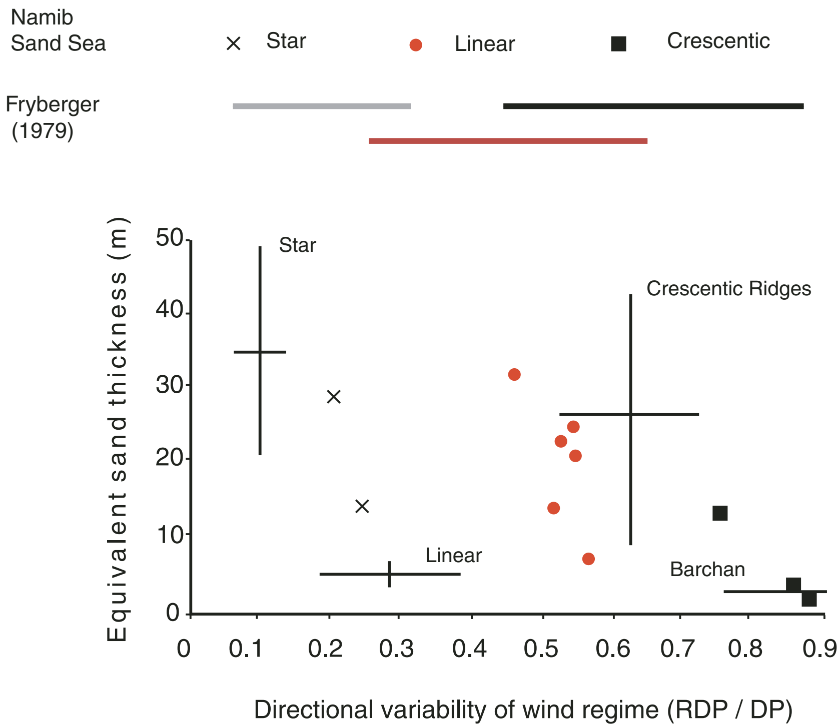

Figure 6. Relations between dune types and wind regimes. Figure from Lancaster (2005).

Monitoring Methods

Level 1: Visual Observation of Dust Storms

Dust storms (Fig. 7) are defined as severe weather conditions in which visibility is reduced to 1 km or less by blowing dust. The frequency of dust storms is measured by the number of such events in a given time period. The magnitude of dust storms can be assessed by the duration of such conditions. Dust events (also known as dust haze) are conditions when visibility is reduced to 11.3 km or less by dust suspended in the air. Blowing dust is a situation where dust is raised to a height of 2 m or more by strong winds, but does not reduce visibility to less than 1 km. Figure 8 provides an example of visibility reduction as a result of a dust storm.

First order meteorological stations may record these conditions as part of their normal schedule of hourly observations. Such data have been used to assess the frequency of dust storms in relation to climatic parameters, such as annual and seasonal precipitation (e.g., Bach et al., 1996; Brazel, 1989; Goudie, 1983; Goudie and Middleton, 1992; MacKinnon et al., 1990; Middleton, 1989). In many areas, dust storm frequency increases in the period following years of lower than average rainfall, although direct correlation between drought conditions and dust storm frequency is not always evident.

Equipment required. No equipment is required.

Complexity. The complexity of this method is very low; it can be conducted by a single observer

Cost. The cost is very low. No instrumentation is required, except for wind speed measurements.

Methodology. Monitoring of dust storms can be undertaken at selected locations where dust storms are known to occur and suitable landmarks exist for visibility determinations. Landmarks at 1 km and 11.3 km distance from the observation point should be identified, and the time and date of dust conditions should be recorded, as well as any relevant meteorological conditions (such as wind speed) and site conditions (such as vegetation cover). The number of dust events and their duration should be recorded on a monthly and annual basis and compared to rainfall and antecedent vegetation conditions.

Timing. Timing is event driven.

Level 2: Camera Stations (Still and Video)

Remotely activated camera stations can be used to image the time, location, and characteristics of dust plumes.

Equipment required. A camera station is required.

Cost. The cost is moderate—around $3,000 to $4,000 per station. (All amounts listed herein are U.S. dollars.)

Complexity. Stations are moderately complex to set up and maintain. Technical assistance is required for set up.

Methodology. Video cameras can be used as they are at Owens Lake, California, by the Great Basin Unified Air Pollution Control District, but their resolution and data capacity are limited. For real-time images see http://www.gbuapcd.org/dustcam.htm. Digital still camera stations have been used to monitor dust storms in the Mojave National Preserve since 2000 (Tigges et al., 2001). The stations automatically acquire digital color images of dust storms, with the cameras triggered by wind speeds above a predetermined threshold. The images are used to

TABLE 1. VITAL SIGNS: AEOLIAN PROCESSES AND FEATURES

Indicator	Methods	Expertise	Technical needs	Cost	Labor
Vital sign 1: Frequency and magnitude of dust storms	Level 1: Visual observation of dust storms	SCA/volunteer	None	Low	1 person
	Level 2: Camera stations (still and video)	Scientist/SCA	Needed for set up	Medium	1 person
	Level 3: Visibility sensors	Scientist	Needed for set up	High	1 person
Vital sign 2: Rate of dust deposition	Level 1: Dust traps	SCA/volunteer	None	Low	1 person
Vital sign 3: Rate of sand transport	Level 1: Estimate rate from wind data	Scientist/SCA	None	Low	1 person
	Level 1: Abrasion stakes	SCA/volunteer	None	Low	1 or 2 people
	Level 2: Sand traps	Scientist/SCA	Needed for set up	Medium	1 or 2 people
	Level 3: Electronic sand transport sensors (e,g., Sensit)	Scientist	Needed for set up	High	1 person
Vital sign 4: Wind erosion rate	Level 1: Lowering of affected surfaces (erosion pins)	SCA/volunteer	None	Low	1 or 2 people
	Level 2/3: Dust concentration measurements	Scientist	Needed for set up	High	1 person
Vital sign 5: Changes in total area occupied by sand dunes	Level 1: Sketch area on topographic map	SCA/volunteer	None	Low	1 person
	Level 2: GPS Survey	Scientist/SCA	GPS	Low	1 or 2 people
	Level 2/3: Aerial photographs and/or satellite images	Scientist	GIS required	Moderate	1 person
Vital sign 6: Area of stabilized and active dunes	Level 1: Delineate areas on topographic map	Scientist/SCA	None	Low	1 person
	Level 2: GPS Survey	Scientist/SCA	GPS	Low	
	Level 3: Aerial photographs and/or satellite images	Scientist	GIS	Moderate	1 person
Vital sign 7: Dune morphology and morphometry	Level 1: Describe major dune types and their characteristics	Scientist/SCA	None	Low	1 person
	Level 2: Aerial photographs or satellite images	Scientist	GIS	Moderate to high	1 person
	Level 3: Digital elevation models	Scientist	GIS	Moderate to low	1 person
Vital sign 8: Dune field sediment state (supply, availability, mobility)	Level 1/2: Identify and describe sources of sediment using existing geologic and sedimentary information	Scientist/SCA	None	Low	1 person
	Level 3: Satellite image processing and modeling	Scientist	GIS	High	1 person
Vital sign 9: Rates of dune migration	Level 1: Field survey	SCA/volunteer	None	Low	1 or 2 people
	Level 2: GPS Survey	Scientist/SCA	GPS	Low	1 or 2 people
	Level 3: Aerial photographs or satellite images	Scientist	GIS	Moderate to low	1 person
Vital sign 10: Erosion and deposition patterns on dunes	Level 1: Repeat photography	SCA/volunteer	None	Low	1 or 2 people
	Level 1: Erosion pins	SCA/volunteer	None	Low	1 person
	Level 3: Topgraphic survey	Scientist/SCA	Surveying/GPS	Moderate	1 or 2 people

Note: GPS—Global Positioning System; SCA—Student Conservation Association.

Figure 7. Dust Storm, Iraq.

Figure 8. Reduced visibility from major dust storm in West Texas, 15 December 2003. Compare with normal clear day (inset). Photographs by Jeff Lee, Texas Tech University.

identify the locations from which dust particles become airborne, the direction and intensity of the dust event, and the meteorological conditions at the time, in conjunction with Climate Impact Meteorological (CLIM-MET) sites (http://climchange.cr.usgs.gov/info/sw/clim-met/) in the area. The system is placed on top of a mountain to provide views to sites of dust emission at distances of 9–20 km. This system is made up of several off-the-shelf components, and several components that were designed and built in-house. Together they perform the task of automatically recording digital images from an unmanned remote location, with recording triggered by wind speed sensors, controlled by a data logger. Images are recorded on a compact flash card with date and time information, for subsequent correlation of images and meteorological data.

The number of dust events and their duration should be recorded on a monthly and annual basis and compared to rainfall and antecedent vegetation conditions.

Timing. Timing is event driven.

Level 3: Visibility Sensors

Automated sensors can be used to estimate the reduction in visibility due to blowing dust, and therefore provide information on the timing, magnitude, and frequency of dust events.

Equipment required. A visibility sensor and a data logger are needed. The instrument should be co-located with other meteorological instruments, including anemometers, to establish the conditions for dust generation and transport.

Complexity. This method requires technical assistance to set up; it is simple to maintain thereafter.

Cost. This method is expensive. Sensors cost $10,000 (Vaisala), plus $2,000 to $3,000 for setting up the station.

Methodology. A variety of visibility sensing devices measure visibility automatically using the forward scattering of infrared light in air over a range of 10–50,000 m. Normally used at airports and other locations at which visibility measurements are made for safety monitoring, such instruments are commercially available, automated, and self contained. Applications specific to dust monitoring are rare, but a visibility sensor has been deployed in association with a U.S. Geological Survey/Desert Research Institute Desert Winds site at Jornada Experimental Range, New Mexico, for several years, and has routinely collected information on visibility reduction resulting from increased dust content in the air.

Timing. The number of dust events and their duration should be recorded on a monthly and annual basis and compared to rainfall and antecedent vegetation conditions.

VITAL SIGN 2: RATE OF DUST DEPOSITION

The rate of dust deposition can indicate the rate of wind erosion in areas that are upwind of a specific site. Wind-blown dust may be derived from local sources, such as **playas** (dry or ephemerally flooded lake beds), and/or more distant sources, like far-traveled dust from the Sahara and Asia. The rate of dust deposition is measured as mass/area/time.

Wind-blown dust is an important long-term contributor of fine material and ions to soils in arid regions and adjacent areas, where it also affects water quality and human health.

Deposition of dust may have a significant effect on the composition and nature of soils in arid regions and beyond. Far-traveled dust may have a significant effect on soil chemistry and nutrient status (Farmer, 1993). Rates of dust deposition can be measured using a variety of active and passive samplers (Goossens and Offer, 2000).

Monitoring Methods

Level 1: Dust Traps

A convenient and practical method of passive sampling of atmospheric dust deposition has been developed by Marith Reheis of the U.S. Geological Survey (USGS) (Reheis, 1997, 2003; Reheis and Kihl, 1995) and utilized in extensive networks for sampling dust input to soils in the southwestern United States. Similar techniques have been used to monitor dust deposition rates in the Dry Valleys of Antarctica (Lancaster, 2002).

Equipment required. A dust trap and field and laboratory supplies for cleaning the dust trap and collecting samples are needed.

Complexity. The complexity is low.

Cost. The cost is low. Each trap costs less than $50 to set up.

Methodology. The method consists of installing a simple, robust passive dust trap, which is cleaned and emptied periodically. The trap is a coated angel-food cake pan painted black on the outside and mounted on a post ~2 m above the ground (Fig. 9). Glass marbles rest on a circular piece of metal mesh that is fitted into the pan 3–4 cm below the rim. The 2-m height eliminates most saltating sand-sized particles. The marbles simulate the effect of a gravelly surface and prevent dust that has filtered or washed into the bottom of the pan from being blown away. The dust traps are fitted with two metal straps looped in an inverted basket shape, and the top surfaces of the straps are coated with a sticky material to discourage birds from roosting. At the chosen monitoring interval, the deposited particles are removed by rinsing the pan, the screen, and the marbles in de-ionized water into a 1 L plastic bottle (see Reheis [2003] for full details of trap construction and field procedures).

In the laboratory, the sample is slowly dried at ~35 °C in large evaporating dishes or beakers; coarse organic material is also removed during this process. The mineral matter remaining can then be weighed. Subsequent physical and chemical analyses on dust samples include: (1) moisture content, (2) organic matter, (3) soluble salts, (4) total carbonate (calcite plus dolomite), and (5) grain size. Other chemical analyses such as phosphorus fractions, strontium and other isotopes, elemental and mineralogical composition, and magnetic properties can be performed on selected samples, depending on sample size and monitoring or research needs.

Following the definitions of Reheis and Kihl (1995), **total aeolian flux** is defined as the rate of deposition of material in

Figure 9. U.S. Geological Survey Reheis Dust Trap. Photo by Marith Reheis, USGS.

grams per square meter per year (g $m^{-2}yr^{-1}$). This can be divided into two components: "dust" flux, which comprises material <50 µm in diameter (silt and clay size), and "sand," which is material >50 µm in diameter. The rate of aeolian deposition is calculated as follows: aeolian deposition rate (g $m^{-2}yr^{-1}$) = mass of dust retained on filter (g) * 1/area of dust pan (m^2) * time exposed (yr).

Timing. Measurement frequency should be annual or semi-annual (to distinguish seasonal changes in dust flux).

VITAL SIGN 3: RATE OF SAND TRANSPORT

The rate of sand transport on sandy surfaces is an indicator of the activity of aeolian processes in an area. Rates of sand transport in relation to wind speed have been determined empirically in wind tunnel studies (Lancaster, 1995). Measurements of sand transport rates in natural settings are much less common (except perhaps in coastal areas), and long-term monitoring studies of sand transport rates are rare.

Monitoring Methods

Level 1: Estimate Sand Transport from Available Climatological Data

Providing that quality wind data are available, sand transport rates may be estimated from wind speed data measured at meteorological stations using one of a number of empirical and theoretical equations (see reviews in Pye and Tsoar, 1990; Sarre, 1987). These rates are, however, *potential* rates, because actual sand transport rates may be reduced by the availability of suitable sediment for transport, presence of vegetation or other elements, surface moisture, crusting, and cohesion of the surface.

Equipment required. This method requires access to pre-existing wind records.

Complexity. The complexity is low.

Cost. The cost is low.

Methodology. One of the most widely used equations for estimating potential sand transport from wind data is the one developed by the USGS (Fryberger, 1979), with modifications and cautions discussed by Bullard (1997). The "Fryberger method" also provides classification schemes for characterizing the energy and directional variability of wind regimes. The method has been widely used to characterize aeolian sand transporting conditions (e.g., Sweet et al., 1988).

The Fryberger method only considers winds above a threshold velocity for sand movement and weights these winds in recognition of the fact that stronger winds are proportionately more effective in transporting sand than weaker winds. Thus:

$$q \propto V^2 \left(V - V_t\right)/100$$

where q is the rate of sand transport, V is the wind velocity at 10 m height and V_t is the impact threshold for transport measured at 10 m. This weighting equation is then calculated for all wind speed categories above the threshold and applied to the percentage frequency of these wind speed categories so that:

$$Q \propto V^2 (V - V_t) t$$

where Q is the rate of sand drift (expressed in vector units), and t is the percentage frequency of winds in that wind speed category.

The total Q for each wind direction and the total for a station are obtained by summation to give the sand "drift potential," or **DP**; and the vector sum or resultant sand drift (RDP) magnitude and direction are obtained by vectoral summation. The DP is a measure of the total wind energy of a location, whereas the ratio between RDP and DP is a measure of the directional variability of the wind regime, which has been widely noted as a major control of the type of sand dune in an area (Fig. 6). Full details of the methods are contained in Fryberger (1979). The original method was based on the use of wind speeds recorded in knots. Bullard (1997) cautions the user and provides information on the use of the weighting factors for winds recorded in other units. Saqqa and Saqqa (2007) provide a simple computer program for estimating sand transport potential. Figure 10 shows an example of a "sand rose" calculated using the Fryberger method, as well as an example of monthly changes in drift potential.

Timing. This method should be performed annually or monthly.

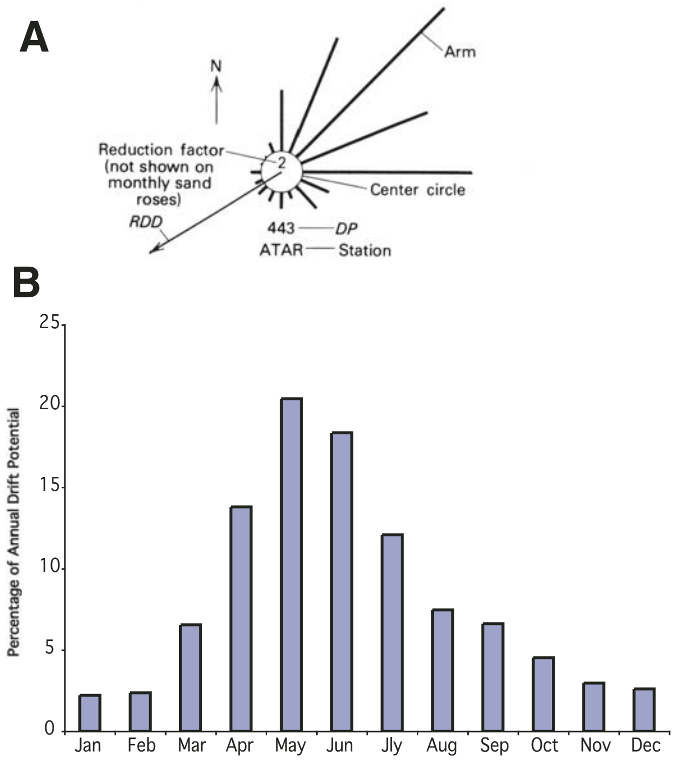

Figure 10. (A) Example of a "sand rose" developed using the Fryberger (1979) method. (B) Monthly variations in drift potential, Palm Springs, California.

Level 1: Abrasion Stakes

An estimate of the rate of wind transport of sand from different directions can be derived from observations of the removal of layers of paint from wooden or aluminum stakes, as used in Pangnirtung National Park, Baffin Island, Canada (McKenna Neuman and Gilbert, 1986).

Equipment required. 1–2-m-high aluminum or wooden poles are needed.

Complexity. The complexity of this method is low.

Cost. The cost of this method is low.

Methodology. The poles should be set up in areas known to experience sand transport. Each pole is painted with eight layers of exterior enamel paint of different colors. Exposure of paint of different colors at different heights and orientation on the stake gives a relative estimate of the intensity of sand transport by different wind directions. This method will work best when sand transport is at a high intensity and thus able to scour paint off the poles.

Timing. Timing should be annual or seasonal.

Level 2: Sand Traps

A wide variety of sand traps have been developed to measure rates of sand transport in laboratory and field settings. See Goossens et al. (2000) and Nickling and McKenna Neuman (1997) for a review of different trap designs.

Equipment required. Sand traps, a balance for weighing sand, and collection bags are needed.

Complexity. The complexity is low to moderate.

Cost. The cost is low. Each Fryrear trap costs approximately \$80 (see below).

Methodology. Long-term monitoring of sand transport rates using traps requires that the traps be robust and self-orienting into winds from different directions. Although many different types of traps have been developed, few can withstand long-term exposure and maintain collection efficiency. An efficient and robust passive sand trap was designed by the U.S. Department of Agriculture (Fryrear, 1986) (Fig. 11). (See http://www.fryreardustsamplers.com/BSNE.html.) This type of trap has been used extensively for time-integrated measurements of sand-size particles moving in saltation in harsh environments (Gillette et al., 1997b; Gillette, 1999; Gillette and Chen, 2001) and for long-term monitoring (Lancaster and Helm, 2000; Tigges et al., 1999). These passive collectors maintain a collection efficiency of ~90% for a wide range of wind speeds (Shao et al., 1993).

The traps can be exposed at a single height (typically 10 cm) or at multiple heights (spaced logarithmically, as in Fig. 11). They may be emptied of sand at any desired interval, taking care that the trap is not filled completely, and the contents weighed. The total horizontal flux of sand can be calculated using the approach of Gillette and Chen (2001). The sand traps should be co-located with wind speed and direction sensors.

Timing. Timing should be weekly or monthly, depending on the rates of sand transport to be expected.

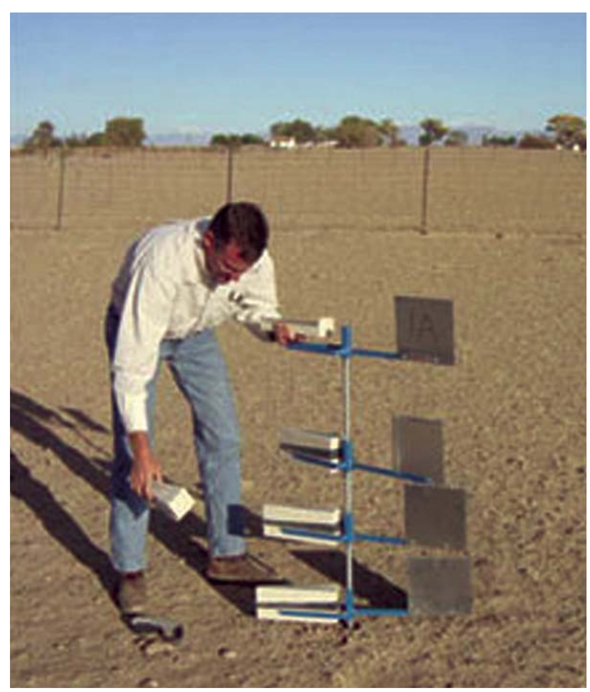

Figure 11. The Big Spring Number Eight sand trap (from http://www.fryreardustsamplers.com/bsne.html).

Level 3: Electronic Sand Transport Sensors

Electronic sand transport sensors have been developed to allow remote monitoring of sand transport rates in conjunction with measurements of wind speed and other parameters. The devices operate on a piezo-electric principle, in which sand grains impact a protected crystal, which sends a signal recording the number and kinetic energy of grain impacts (Gillette and Stockton, 1986). One device is the Sensit™ (http://www.sensit.com/). In practice, the kinetic energy signal from this device has been difficult to interpret. The particle count signal is calibrated by the manufacturer or in a wind tunnel with a known mass flux of sand.

Equipment required. A sand transport sensor, data logger, anemometer, and wind vane are needed.

Complexity. The complexity is moderate to high. Technical knowledge is needed to install and maintain devices and interpret data.

Cost. The cost is moderate to high; Sensits are about $2,000 each, Safires about $700 each. A data logger and associated instrumentation (e.g., anemometer and wind vane) are required, adding a further $2,000–$3,000 to the cost.

Methodology. The Sensit device has been widely used for sand transport monitoring (Fig. 12). Examples include the USGS Desert Winds (Tigges et al., 1999) and CLIMET programs (http://climchange.cr.usgs.gov/info/sw/clim-met/) and the Great Basin Unified Air Pollution Control District at Owens Lake, California. Sensits should be co-located with anemometers and wind vanes to ensure sand transport is monitored in conjunction with relevant wind data. A newly developed alternative to the Sensit are the Saltation Flux Impact Responders (Safires). Baas (2004) evaluated the performance of these piezoelectric crystal type instruments. He found that the Safire presents a minimal obstruction to the wind flow and provides high-frequency omni-directional measurements at a relatively low cost compared with other piezoelectric type sensors. Although Safires have been used in coastal dune settings in the Netherlands (Arens, 1997), they have not been used for long-term monitoring.

Figure 12. Sensit sand transport sensor at Owens Lake, California. Senor is mounted so that height of crystal above surface can be adjusted if surface changes.

Timing. Data should be downloaded monthly.

VITAL SIGN 4: WIND EROSION RATE

The action of wind on exposed sediments and friable rock formations causes erosion (abrasion) and entrainment of sediment and soil particles. Wind erosion physically removes the lighter, less dense soil constituents such as organic matter, clays, and silts. Thus it removes the most fertile part of the soil and lowers soil productivity (Leys, 1999). The rate of wind erosion of a given area is a direct measure of the loss of the surface soil and its contained nutrients, seeds, and soil materials. In addition to lowering of the surface, some authors have noted changes in soil texture as a result of wind erosion. Although these mainly apply to agricultural fields, some coarsening of natural surfaces may occur as a result of wind erosion.

Monitoring Methods

Level 1: Lowering of Affected Surfaces

Equipment required. Erosion pins (e.g., rebar) and a measuring tape are needed.

Cost. The cost is low.

Complexity. The complexity level is low.

Methodology. The rate of lowering of affected surfaces, such as sand sheets, playa surfaces, and alluvial flats may be monitored using erosion pins at strategically located sites. Monitoring of erosion using erosion pins can be as simple as using lengths of rebar hammered into the ground and measuring the exposure of the pin relative to the ground surface at regular intervals. Such methods have been used to monitor wind erosion rates at Jornada Experimental Range and Owens Lake (Fig. 13). When placing the pins, care should be taken to choose a representative sample of the area. Multiple pins per site are useful to estimate local variability in rates. The resolution of this method is relatively low; it is difficult to measure surface changes of less than 10 mm.

In addition, qualitative estimates of wind erosion can be made via the degree of exposure of roots and creation of residual pedestals of soil by wind erosion.

Timing. Timing should be monthly or annually.

Figure 13. Erosion pins for monitoring dune dynamics, Namib Desert.

Level 2 and 3: Measurements of Dust Concentration Downwind of Affected Area

Measurements of dust concentration in the air downwind of an eroding area can provide information on the mass of fine material eroded from that area.

Equipment required. Dust concentration measuring devices (e.g., DustTrak) are needed.

Cost. Costs are very high. MiniVol is $3,500; DustTrak is $3,000 to $4,000; TEOM is $25,000 or more.

Complexity. The complexity level is high to very high. Skilled technical support is required to install and maintain TEOM instruments. DustTrak can be operated with minimal training.

Methodology. The vertical profile of dust concentration above the surface is a measure of the amount of fine particulate matter being emitted from a surface (the vertical flux of dust). Typically, dust concentration shows an exponential decrease in height above the emitting surface, due to dispersion of the dust by atmospheric turbulence. The gradient (slope) of the profile is proportional to the rate of emission. Measurements of concentration profiles require sophisticated instrumentation and are a research, rather than a monitoring, technique. They apply only to the conditions being studied (Gillette et al., 1997a; Gillette et al., 1997b; Nickling et al., 1999).

An estimate of dust emission rates can be obtained via measurements of particle concentrations downwind of the eroding area. Such measurements are made using one of a wide variety of devices used to measure ambient air quality and are usually targeted toward a specific particle size (e.g., PM10, or 10 µm). Such devices employ a pump, which draws air at a precisely calibrated rate through a filter, on which the dust collects for subsequent weighing and analysis. Typical examples of these devices are the HiVoL and MiniVol samplers used to collect dust to ensure compliance with federal (Environmental Protection Agency) and state air quality standards (Chow, 1995). Newer devices include the DustTrak (Fig. 14), which employs a laser beam to measure dust concentrations in a chamber within the instrument (http://www.tsi.com/Product.aspx?Pid=11). The TEOM, Tapered Element Oscillating Microbalance, (http://www.rpco.com/products/ambprod/amb1400/index.htm) is another, more costly device, and it is the only real-time particulate monitor that directly and continuously measures the mass of particulates collected on a filter and provides continuous particulate concentration data. Such devices can be installed in critical areas (such as Owens Lake, California). They also provide information on the magnitude and frequency of dust storms via changes in dust concentration over time.

Timing. Timing should be event based, or data can be downloaded weekly.

VITAL SIGN 5: CHANGES IN TOTAL AREA OCCUPIED BY SAND DUNES

The total area occupied by sand dunes is an indication of the long-term supply of sediment to an area. Changes in the total area and location covered by dunes will, over time, reflect the long-term sediment budget of an area, as well as the degree to which the dune field as a whole is migrating. Decreases in the area covered by dunes as well as the size of dunes (see below) reflect a negative sediment budget in which sediment is being lost from the dune field faster than it is supplied. Conversely, an increase in dune size or area of dunes may indicate a positive sediment budget in which the supply of sediment exceeds losses.

Figure 14. DustTrak monitoring device deployed at Jornada Experimental Range, NM. (Photograph by W.G. Nickling.)

Monitoring Methods

Level 1: Delineation on a Map of Area Occupied by Dunes

Measurements or estimates of the area occupied by dunes are necessary steps to establishing a baseline for monitoring changes in dune fields.

Equipment required. Maps and/or orthophotograph quads and a planimeter are needed.

Cost. The cost is low.

Complexity. The complexity level is low.

Methodology. The most straightforward method of assessing changes in dune area is to delineate the area(s) covered by dunes on published topographic maps or similar products. The total area(s) covered by dunes can be estimated using a planimeter or by measuring dune field width and length. If maps compiled at different dates are available, then comparisons of dune field area and position can be made. In many cases, however, the area(s) of dunes depicted on USGS 7.5′ quad (1:24,000 scale) topographic maps is very generalized. A more accurate estimate of dune field area can be obtained from the digital orthophoto quarter-quadrangles (DOQQ), which are compiled directly from aerial photographs. It should be noted that this method can only provide information on dune field area for the dates when the maps were compiled, which may be irregular or infrequent. If a more frequent assessment of dune field area is required, then Level 2 or Level 3 methods should be used.

Timing. Intervals should be determined by available maps and frequency of revision.

Level 2: Global Positioning System (GPS) Survey

In recent years, low-cost, handheld GPS units have provided a simple, rapid, and accurate way to document geographical areas. Field traverses of the margins of dune fields can provide an accurate outline of the area.

Equipment required. A handheld GPS unit and maps and/or orthophotograph quads are needed.

Cost. The cost of this method is low.

Complexity. The complexity level is low to moderate.

Methodology. Field traverse of the perimeter of the area of dunes are conducted. Coordinates of key points are determined by GPS. The coordinates of these points can then be transferred to a topographic map base or geographic information system (GIS). This method may be time-consuming for larger dune fields and is best suited to small areas of dunes where an accurate mapping of the area of dunes is required at a frequency greater than that of map revisions or new aerial photograph or satellite coverage.

Timing. This method can be performed at annual or longer intervals.

Levels 2 and 3: Comparison of Areas of Dunes on Aerial Photographs and/or Satellite Images

In many areas, a long history (as much as 70 years) of dune field dynamics can be compiled by comparing the area and position of dune field margins on vertical aerial photographs or satellite images taken at different times.

Equipment required. Aerial photographs, a scanner, access to a GIS application are needed.

Cost. The cost is moderate to high, depending on the cost of aerial photograph coverages.

Complexity. The complexity level is high; this method requires knowledge of GIS applications.

Methodology. At the simplest level, transparency sheets (made of mylar, for example) are laid over the photographs. The area can be delineated on the transparency, and the information transferred to a topographic map using visual comparison to features common to both. More accurate and more valuable information can be gained by scanning the images, correcting their geometry in a GIS and compiling coverages of dune field area at different times. Geometric corrections are necessary to co-register the images in a common geographic reference frame. The GIS can then be used to generate dune areas and to estimate changes in area and/or position over time (Lancaster, 1997; Lancaster et al., 2001).

Satellite image data (e.g., Landsat) can also be used to generate data on dune field dynamics. Because their spatial resolution is in tens of meters, they are best used for larger dune areas.

High-resolution satellite image data are available, but these data are expensive and have a limited temporal and spatial availability. Landsat satellite data are also only available back to 1973, so information from this source is only relevant to the past 30 years or so. Despite these limitations, satellite data have been used to provide a long-term view of the dynamics of some dune fields, such as Great Sand Dunes (Janke, 2002; Marîn et al., 2005).

Timing. Intervals should be determined by dates of aerial photograph coverages.

VITAL SIGN 6: AREA OF STABILIZED AND ACTIVE DUNES

The active area of dunes, bare sand surfaces or migrating (mobile) dunes, compared to the inactive area (stabilized by vegetation) is a valuable indicator of the response of both inland and coastal dunes to changes in sediment supply and mobility. In coastal dune areas, the primary control of dune activity is the supply of sediment, because many coastal dunes are located in areas where the climate permits growth of vegetation. Thus, many coastal dunes are very active close to the supply of sediment at the coast and become progressively less active inland as sediment supply decreases.

In inland dune areas, the primary control of dune activity is climatic. Dune mobility can be characterized by the ratio between wind energy (W) and the effective precipitation (P/PE) (Lancaster and Helm, 2000). Thus, dunes can be active in areas that are characterized by windy conditions, although precipitation can be quite high. The relations between wind energy and effective precipitation for dune areas in the western United States are shown in Figure 15.

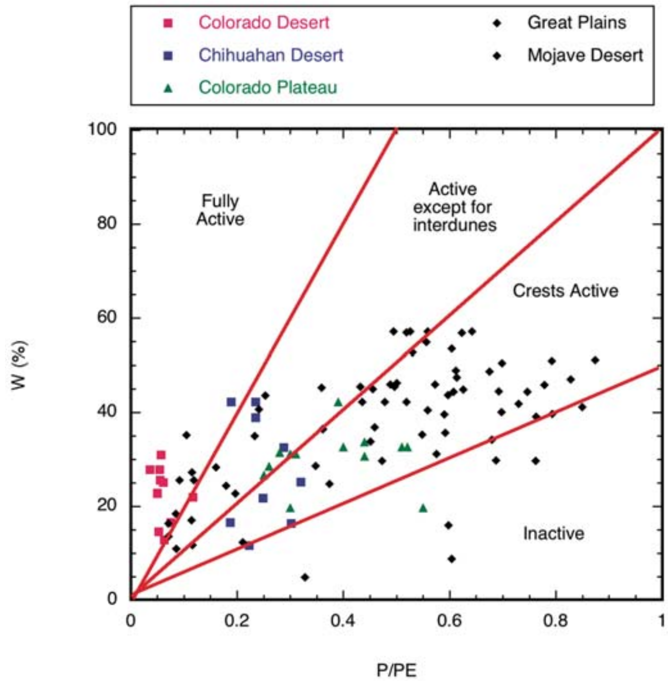

Figure 15. Dune mobility index values for locations in the western United States compiled from data provided by author and D. Muhs (U.S. Geological Survey).

Monitoring Methods

Level 1: Delineation of Area Occupied by Active and Inactive Dunes on Topographic Maps

Equipment required. Aerial photographs and topographic maps are needed.

Cost. Costs are low to moderate, depending on the cost of aerial photograph coverages.

Complexity. The complexity level is moderate.

Methodology. The areas covered by active and vegetation-stabilized dunes can be interpreted from aerial photographs or field survey and transferred to a topographic map base. On most aerial photographs, bright tones indicate bare (active) sand, whereas progressively darker tones indicate vegetation-stabilized dunes and sand surfaces. Field checking is desirable to develop accurate classification of areas. These methods have been used to map areas of active and inactive dunes in many areas (Forman et al., 2006; Lancaster, 1997; Paisley et al., 1991)

In some cases, historical records of dune conditions developed by land surveys and explorations can be a valuable source of information on very long-term trends (Muhs and Holliday, 1995).

Timing. Timing should be determined by the dates of aerial photograph coverages.

Level 2: GPS Survey

Equipment required. A handheld GPS unit is required.

Cost. The cost of this method is low.

Complexity. The complexity level is low to moderate (assuming that a GPS unit is available).

Methodology. Field traverses of the margins of active and inactive dune areas can provide an accurate outline of the area of dunes in different states, once the coordinates of key points are determined by GPS survey transferred to a topographic map base. This method may be time-consuming for larger dune fields and is best suited to small areas of dunes where an accurate mapping of the area of dunes is required at a frequency greater than that of map revisions or new aerial photograph coverage.

Timing. Intervals should be annual or decadal.

Levels 2 and 3: Comparison of Aerial Photographs and/or Satellite Images

Equipment required. Aerial photographs or satellite images and access to GIS application are needed.

Cost. The cost of this method is moderate, depending on the cost of aerial photograph coverages and satellite images.

Complexity. This method is highly complex; it requires knowledge of GIS applications and image analysis.

Methodology. In many areas, a long history (as much as 60 years) of dune field dynamics can be compiled by comparing the area and position of areas of active and inactive dunes on vertical aerial photographs. At the simplest level, transparency sheets (made of mylar, for example) are laid over the photographs. The area can be delineated on the transparency, and the information transferred to a topographic map using visual comparison to features common to both. More accurate and more valuable information can be gained by scanning the images, correcting their geometry in a GIS and compiling coverages of dune field area at different times. Geometric corrections are necessary to co-register the images in a common geographic reference frame. The GIS can then be used to generate dune areas and to estimate changes in area and/or position over time. Satellite image data can also be classified to develop information on vegetation and land cover characteristics and to determine changes in the area of active and inactive dunes. For example, Janke (2002) was able to show that dune grasses were being replaced by semi-desert scrub on the west side of Great Sand Dunes, thereby reducing sand mobility.

Timing. Intervals are determined by dates of aerial photograph and/or satellite image coverages.

VITAL SIGN 7: DUNE MORPHOLOGY AND MORPHOMETRY

Dunes occur in a variety of morphological types in self-organized patterns as a response to the wind regime (especially its directional variability) and the supply of sand. Parabolic dunes and nebkhas are controlled by the presence of vegetation. Sand dunes occur in four main morphologic types (Figs. 5 and 6; Table 2): Crescentic (transverse), linear, star, and parabolic. The type of dune is therefore an indicator of the characteristics of the wind regime and the amount of sand available for dune construction. Changes in dune morphology over time can provide valuable information about the long-term response of the dune field to climate and sediment supply. For example, a change from parabolic to crescentic dunes could indicate a reduction in vegetation cover, whereas development of parabolic dunes from crescentic types is indicative of increased vegetation cover, as in coastal areas of Israel (Tsoar and Blumberg, 2002). Changes in dune size are a clear indication of increases or decreases in sediment supply and changes in sediment budgets.

TABLE 2. MORPHOLOGICAL CLASSIFICATION OF DUNES

Dunes → Draas, Mega-dunes

Relative Sediment Thickness →

Wind regime complexity ↓

	TRANSVERSE		
	Barchans Dome dunes	Crescentic ridges	Compound crescentic dunes
	LINEAR		
	Simple - Straight - Sinuous	Compound Linear dunes	Complex Linear dunes
	REVERSING		
	STAR		
coarse sand	SAND SHEETS	ZIBARS	
vegetation anchored	NEBKHAS	BLOW OUT DUNES	PARABOLIC DUNES
source bordering	LUNETTES		
topographic influence	ECHO DUNES	FALLING DUNES	CLIMBING DUNES

Note: Modified from Lancaster (1995).

Monitoring Methods

Level 1: Describe Major Dune Types and Their Characteristics

Equipment needed. Maps, aerial photographs, and satellite images of the dune area are needed, as well as access to any previously published work.

Cost. The cost of this method is low.

Complexity. The level of complexity is low.

Methodology. Identification and description of the major dune types occurring in a dune field is a necessary first step to understanding the dynamics of a dune system. The different dune types present should be identified using well-accepted classification schemes (e.g., McKee, 1979a) (Fig. 5, Table 2), and described in terms of their height, width, and spacing. There are numerous studies of dune morphology done in this way (see Lancaster, 1995, for examples), but many dune fields in the United States have not been systematically described.

Timing. This method should be used as needed. Most dune types do not change significantly over time periods of years to decades, and many have remained similar for thousands of years.

Level 2: Map Dune Types and Their Distribution using Aerial Photographs or Satellite Images

Equipment required. Maps, aerial photographs, and satellite images of the dune area are needed.

Cost. Costs are moderate to high, depending on the cost of aerial photograph coverages or satellite images.

Complexity. The complexity level is moderate to high; this method requires knowledge of GIS applications.

Methodology. The goal at this level is to accurately map the different dune types using aerial photographs or satellite images, using a classification scheme as above. In this way, the area occupied by different dune types can be estimated, and changes in dune distribution and/or morphology can be assessed using sequential aerial photograph series. There are numerous examples of the application of these techniques (Andrews, 1981; Lancaster, 1990, 1993; McKee and Moiola, 1975; Sweet et al., 1988).

Timing. Intervals are determined by dates of aerial photograph coverages.

Level 3: Use Digital Elevation Models (DEMs) to Estimate Dune Size and Sediment Volumes

Equipment required. Computing resources and GIS applications are needed.

Cost. Costs are low to moderate, depending on the cost of image data.

Complexity. This method is highly complex; it requires knowledge of GIS applications and data processing.

Methodology. DEMs can be used to estimate dune size, spacing, and sediment volume using GIS software. With these data, it is possible to accurately monitor changes in sand volume that may be occurring as a result of changes in sediment supply. Data may include online digital data (e.g., http://seamless.usgs.gov/) or high-resolution LIDAR (light detection and ranging) data, which may be available from state or local governments, or specifically commissioned.

Timing. Intervals are determined by the dates of DEM or LIDAR coverages.

VITAL SIGN 8: DUNE FIELD SEDIMENT STATE

Dune fields form part of the well-defined regional- and local-scale sediment transport systems in which sand is moved by wind from source areas (e.g., distal fluvial deposits, sandy beaches) via transport pathways to depositional sinks. Dune fields accumulate downwind of source zones at points where wind speed and directional variability change, so that the influx of sand exceeds outflux, resulting in deposition and growth of a dune field. Over long periods of time (decades to centuries and longer) the dynamics of the system are determined by changes in the supply of sediment of a size suitable for transport by the wind; the availability of this sediment for transport, determined by vegetation cover and soil moisture; and the mobility of this sediment, controlled by wind strength. The interactions between these variables can be evaluated in terms of the state of the aeolian system and the limiting factors identified (Kocurek and Lancaster, 1999). Monitoring of the current and past sediment state of a dune field is an aid to understanding how it is responding to stressors.

Monitoring Methods

Level 1 and 2: Identify and Describe the Sources, Transport Pathways, and Depositional Sinks of the System

Equipment required. Maps, aerial photographs, and published reports are needed.

Cost. The cost is moderate to low, depending on the cost of image data. Google Earth is also a good source of data.

Complexity. The complexity level is moderate to high. Some expert knowledge may be required for interpretation of data.

Methodology. Monitoring of basic parameters and how they change over time is essential to assessing the state of any system. A regional survey of the primary and secondary sources of sediment, the transport pathways, and the sinks for sediment (depositional areas) is also valuable for addressing impacts on the system. For example, knowledge of these parameters in the Coachella Valley, California, was a necessary prerequisite for developing a habitat conservation plan for the Coachella fringe-toed lizard (Griffiths et al., 2002).

The sources of sediment, transport pathways and sediment sinks can be identified from published literature and maps, field survey, and aerial photographs, supplemented by mineralogical analyses of sand. Good examples of this approach are Griffiths et al. (2002) and Sharp, (1966).

Timing. This method should be used at decadal intervals.

Level 3: Use Remote Sensing Data to Identify and Track Sand Sources, Transport Pathways and Sinks

Especially in large, complex dune fields, it may be difficult to assess sand sources, transport pathways, and sinks using published studies and limited field surveys. Recent advances in both remote sensing technologies and methods of analysis allow the identification and monitoring of aeolian systems remotely, thus saving many months of field research. These approaches were pioneered in the Gran Desierto of Mexico (Blount and Lancaster, 1990; Blount et al., 1990), and have been followed by more detailed studies of sand sources for Kelso dunes, California (Ramsey et al., 1999) and the Coachella Valley, California (Katra et al., 2009).

Equipment required. Satellite image data, computing resources, and image analysis software are needed.

Cost. Costs are moderate, assuming image data are available.

Complexity. This method is highly complex; expert knowledge is required for image analysis and interpretation.

Methodology. Primary minerals have distinctive characteristics that can be identified in multispectral image data (such as Landsat). This approach uses spectral information on the sub-pixel scale to identify mineral composition and the relative abundance of different primary minerals. Formerly, this was a research technique, but some available image analysis software applications (such as ENVI) include these techniques as part of their suite of image analysis routines. Care should be taken with interpretation of results.

Timing. This method should be performed at decadal intervals.

VITAL SIGN 9: RATES OF DUNE MIGRATION

The rate of dune migration is inversely proportional to dune height and directly proportional to wind speed and sand transport rates. Monitoring rates of dune migration provides valuable and easily understood information on the dynamics of the aeolian system. If the potential exists for dunes to move into areas of concern (by crossing roads or migrating into critical habitats, for example), then monitoring of migration rates can provide valuable information for resource management. There is a long history of studies of dune migration rates and several well-established methodologies, as discussed below.

Monitoring Methods

Level 1: Field Survey of Dune Position Over Time

Equipment required. Marker stakes and a tape measure are needed.

Cost. The cost is very low.

Complexity. The complexity level is low.

Methodology. Where dunes are well defined, rates of migration may be monitored by comparing their position relative to fixed markers, such as stakes driven into the ground. These markers may be placed around the perimeter of isolated dunes or adjacent to the lee face of transverse or parabolic dunes. The position of the dune can be compared to the original stake positions and rates of change determined on a seasonal or annual basis. Such methods have been used at White Sands, New Mexico (McKee and Douglass, 1971), and in Namibia (Bristow and Lancaster, 2004), and elsewhere. The disadvantage of field surveys is the need to continually revisit the monitored dune over the years, and the probability that monitoring stakes may be buried or left behind as the dune advances.

Timing. This should be done annually.

Level 2: GPS Survey of Dune Positions

Equipment required. A differential GPS unit is needed.

Cost. Costs are low, providing that a GPS unit is available.

Complexity. This method is moderately complex; training in use of GPS units is required.

Methodology. Dune migration rates can be determined and monitored very easily with high-precision GPS surveys using a differential GPS unit. Using this methodology, the coordinates (latitude and longitude or UTM coordinates) of the leading edge of a dune (usually the base of a slip face) can be determined with a precision of less than 1 m, which is more than sufficient for annual surveys of dune migration rates. The coordinates for the position of the dune in successive years can then be compared to determine any advance. This methodology has been used to determine dune migration rates in Egypt (Stokes et al., 1999). The outline of the dune can be also surveyed using this method, providing a record of changes in dune morphology over time.

Timing. This should be done annually.

Level 3: Comparison of Dunes on Aerial Photographs or Satellite Images of Different Dates

Equipment required. Aerial photographs and topographic maps are needed.

Cost. Costs are low to moderate, except for computing resources.

Complexity. This method is highly complex; it requires specialist knowledge of GIS and data processing.

Methodology. In this method, the position of dunes at different times is compared using aerial photographs taken at selected intervals. At the simplest level, transparency sheets (made of mylar, for example) are laid over the photographs. The area can be delineated on the transparency, and the information transferred to a topographic map using visual comparison to features common to both. The change in position of the dunes can then be measured on the map and divided by the number of years between the aerial photograph coverages to provide an estimate of dune migration rates. This method has been used extensively in southern California (Haff and Presti, 1995; Long and Sharp, 1964; Sweet et al., 1988) and elsewhere (Finkel, 1959; Hastenrath, 1967; and Slattery, 1990). It works best when the dunes are well-defined and moving fairly rapidly. In general, dune migration rates vary inversely with dune size.

More precise and more valuable information can be gained by scanning the images, correcting their geometry in a GIS and compiling coverages of the position of the dunes at different times. The GIS can then be used to generate maps of dunes at different times and to estimate migration rates. This methodology was used to examine dune and dune field migration rates in the Christmas Valley, Oregon, in support of management of this area by the Bureau of Land Management (Lancaster et al., 2001), and at Great Sand Dunes, where changes in dune migration rates were compared to climate data (Marîn et al., 2005).

Timing. Intervals are determined by the dates of the aerial photographs.

VITAL SIGN 10: EROSION AND DEPOSITION PATTERNS ON DUNES

The pattern of erosion and deposition on dunes provides a record of the response of the dune to airflow patterns and vegetation. Valuable information on the dynamics of the dunes and their response to changes in climate and vegetation can be generated in this way.

Monitoring Methods

Level 1: Repeat Photography

Many changes in the topography and morphology of dunes are complex, and require careful, quantitative topographic survey. A qualitative monitoring of seasonal, annual, or multi-annual changes in dunes can be achieved using repeat photography from fixed camera stations (Livingstone, 1987).

Equipment required. A digital camera and a GPS unit are needed.

Cost. The cost of this method is low.

Complexity. The complexity level is low.

Methodology. Critical areas of dunes, such as advancing dune fronts, are identified, and a camera station with an unobstructed view is established. The camera station is permanently marked and its GPS location recorded. Clear information is needed on the date and time of the photographs, the camera system and focal length of lens used. Photographs or panoramas are repeated on a regular basis.

Timing. This method should be repeated annually.

Level 2: Erosion Pins

Transect lines or grids of erosion pins can be set up across dunes to measure erosion and deposition patterns at certain points on the dunes (Fig. 13). These patterns can then be compared to winds and, if relevant, vegetation cover. This method has been used to monitor changes on a dune in Namibia for over 20 years (Livingstone, 1989, 1993, 2003). Other examples include studies of coastal dune systems (e.g., Arens et al., 2004; Gares, 1990; Gares and Nordstrom, 1995; Jungerius and Verheggen, 1981).

Equipment required. Erosion pins (or stakes) and tape measure(s) are needed.

Cost. The cost is low (after initial set up).

Complexity. The complexity level is low to moderate.

Methodology. Grids or transects of erosion pins are set up across the dune using pins at intervals of 5 or 10 m (or at critical points, such as the base of the slip face). If possible, positions of pins should be surveyed. Measurements from tip of pin to surface should be recorded, as well as the height (exposure) of pin. Changes in the exposure of the erosion pins (less exposure = deposition; increased exposure = erosion) provide a record of dune dynamics.

Timing. This method can be used weekly, monthly, or annually. Shorter intervals provide more precise information and are easier to relate to winds and vegetation conditions.

Level 3: Topographic Survey

Detailed topographic surveys, with a contour interval of 1 m or less can provide very useful data for monitoring dune changes and dune dynamics. These techniques have been used to assess dune changes in several studies, in Oman (Warren, 1988), Namibia (Livingstone, 2003; Ward and von Brunn, 1985); and in coastal blowout dunes in the Netherlands (Arens, 1997; Arens et al., 2004).

Equipment required. Survey instruments (total station) or a differential GPS unit are needed.

Cost. The cost is moderate, assuming that equipment can be borrowed or rented.

Complexity. The level of complexity is moderate to high. Training in surveying is required; analysis of results requires a GIS expert.

Methodology. This type of survey can be carried out using a **total station**, which downloads coordinates to a computer for subsequent plotting in a contouring and mapping program such as Surfer. If a differential GPS unit is available, then similar, but slightly less precise, data can be generated from a detailed GPS topographic survey. Either type of survey can generate data for a digital elevation model, or DEM. Changes can be assessed quantitatively by comparing digital elevation models for different time periods, generating information on areas where changes have occurred and on the volumes and rates of erosion and deposition in these areas.

Timing. This data can be generated at seasonal to annual intervals.

SUMMARY AND RECOMMENDATIONS FOR MONITORING OF VITAL SIGNS

This section provides a statement of the most effective methods for monitoring of the vital signs identified for aeolian processes and landforms.

Vital Sign 1: Frequency and Magnitude of Dust Storms

Providing that personnel are available to record visibility reduction caused by blowing dust, visual observation and recording is the preferred and most cost effective method for monitoring of dust events. In cases where the site is remote, then automated camera systems are the preferred methodology.

Vital Sign 2: Rate of Dust Deposition

The USGS dust trap method is reliable and simple, and provides a valuable record of dust deposition over periods of years to decades.

Vital Sign 3: Rate of Sand Transport

Estimation of potential sand transport rates from wind data is a necessary first step for monitoring of sand transport rates. This also provides data that can be compared with other areas. Long-term field monitoring of transport rates using the Big Spring Number Eight (BSNE) trap provides a valuable record, if the site(s) are carefully chosen.

Vital Sign 4: Wind Erosion Rate

Use of erosion pins and other topographic data can provide a good documentation of wind erosion rates for specific areas.

Vital Sign 5: Changes in Total Area Occupied by Sand Dunes

Although more complex and expensive, a GIS approach is far superior to other methods for estimation of dune field changes, providing quantitative data that can be used in conjunction with climate records to understand long-term aeolian dynamics.

Vital Sign 6: Area of Stabilized and Active Dunes

Mapping of active and stabilized dunes using satellite image data is an excellent method. When used in combination with a

GIS, this approach is far superior to other methods for estimation of dune field changes, providing quantitative data that can be used in conjunction with climate records to understand long-term aeolian dynamics.

Vital Sign 7: Dune Morphology and Morphometry

Use of aerial photographs and/or satellite images is the preferred method for describing dune morphology and documenting any changes that may occur. Although more complex and expensive, a GIS approach is far superior to other methods, providing quantitative data to understand long-term aeolian dynamics.

Vital Sign 8: Dune Field Sediment State

Valuable data on sediment state can be obtained using a descriptive approach, with limited analyses of samples for bulk mineralogy.

Vital Sign 9: Rates of Dune Migration

Rates of dune migration are best determined using repeated GPS surveys, or if a long-term historical record is needed, by comparison of dune positions on aerial photographs or satellite images. In either case, a GIS approach for data recording and synthesis is desirable.

Vital Sign 10: Erosion and Deposition Patterns on Dunes

Repeat photography and simple field surveys can provide valuable information and are simple to set up and repeat.

STUDY DESIGN

General Principles

Any study design should consider the goals of the monitoring, and therefore what process or landform will be studied, why it should be monitored, and for how long. Short-term observations of change are useful, but long-term monitoring is very valuable, though it involves a long-term commitment of resources. The personnel and other resources available will largely determine the methods employed. In general, simple methods regularly applied will yield good results. As far as possible, monitoring programs should strive for quantitative and reproducible results. All data gathered should be assessed critically after two or three measurement intervals to determine: (1) whether changes can be detected; and (2) whether the data can be explained and understood using knowledge of the process or landform being monitored. Adjustments to the monitoring program then can be made as needed, but radical changes should be avoided. It is always useful to have an outside "expert" to act as a consultant.

An Example Program to Monitor Movement of Small- to Moderate-Size Inland Dunes

Monitoring of the rates of movement of inland dunes can provide a sensitive overall assessment of the activity of an aeolian sand system and its response to natural and anthropogenic stressors. An ideal program will combine both short-term (months to years) and long-term (years to decades) monitoring of dune migration rates. Migration rates should be compared to climatic data on all time scales.

Major Project Milestones

1. Determine resources available for monitoring and select appropriate methods to be used. As discussed above, the best techniques for short-term monitoring are field survey using fixed markers or a differential GPS survey; for long-term measurements, use aerial photographs or satellite images taken on different dates.
2. Ensure that relevant hourly wind speed and direction data are available for the monitoring site. Upgrade existing weather stations or install new equipment for the monitoring program.
3. For short-term measurements: select dunes to be monitored. Dunes should be selected to be representative of the size and morphological type found in the study area. If dune types vary significantly, then choose measurement sites for each type. Ensure that monitoring sites are easy to access and not likely to be disturbed by animals or people. Set up fixed points and benchmarks. Allocate resources for monthly or seasonal measurements.
4. For long-term monitoring: Acquire baseline image data and incorporate into a GIS system.
5. For short-term monitoring: make monthly or seasonal measurements and enter these data into a database. Produce graphics showing changes over time.
6. For long-term monitoring: compare dunes on images acquired annually. Produce maps of changes from year to year.
7. After one year, assess short-term monitoring data (if data are collected monthly). Compare rates of movement to wind and other climate data. Determine trends. Are there seasonal differences in migration rates? Do these relate to variations in wind speed and/or direction over the year? Determine optimal timing of measurements and adjust program accordingly. It may be that dune movement is slow enough that annual or seasonal measurements are sufficient. Report results to scientific and management communities. Provide public outreach.
8. After 5 years, assess long-term monitoring data on migration rates by comparing image data from different years. Determine trends, if any. Are there inter-annual differences in migration rates? Do these relate to variations in wind speed and/or direction, or to changes in precipitation (and therefore vegetation cover)? Report results to scientific and management communities.

CASE STUDIES

There are relatively few long-term monitoring studies of aeolian processes and landforms, in part because of the remote nature of many desert regions, and in part because of the perception that geomorphic change is slow in deserts. Good examples include the USGS Desert Winds project (now in part administered by the Desert Research Institute), the USGS dust trap–monitoring study in the southwestern United States, and a decades-long monitoring of cross-sectional and morphologic change on a Namibian linear dune. Common to the latter two projects is a relatively simple and robust methodology. This simplicity ensures that ongoing costs of monitoring are low, using a clearly targeted process or landform and a dedicated principal investigator, who has maintained the monitoring network over many years. Many of the problems encountered by the Desert Winds project stem from the overabundance of data collected and the lack of a clearly defined purpose for the monitoring.

Long-Term Monitoring of Sand Transport and Climatic Parameters: The Desert Winds Project

The Desert Winds Project was set up by the USGS in the early 1970s and was designed to permit remote monitoring of aeolian processes (McCauley et al., 1984). Goals of the monitoring network were: (1) to provide a long-term database for understanding the range of environmental conditions that can be expected to occur normally in arid and semiarid areas of the desert southwest; (2) to acquire baseline data to assess changes in the desert such as changes in vegetation, migration of sand, and increased dust storms that may occur due to climate change in desert regions; and (3) to acquire data for field-checking remotely sensed image data of various surfaces, so that regional models can be developed for monitoring land surface changes over time.

Each station was equipped with anemometers at three heights (1.2, 2.7, and 6.1 m), a wind vane at 6.1 m, temperature and humidity sensors at 1.2 and 6.1 m, and a tipping bucket rain gauge. Transport of sediment by wind is monitored by BSNE sand traps (Fryrear, 1986) mounted at 0.05 or 0.15 m, 0.50 m, and 1.0 m, together with a Sensit piezo-electric sand transport sensor at 0.05 or 0.15 m above the surface. Full details of the instrumentation and operation of the stations are given in Tigges et al. (1999). With the exception of the BSNE traps, all sensors are scanned at one-second intervals with 6-minute averages of the anemometer, wind vane, and Sensit readings, together with 12-minute average temperature, as well as hourly humidity, and precipitation. Data were uploaded via the GOES satellite each hour until the mid 1990s, when the original equipment was replaced by data loggers, which are downloaded on a monthly basis. Currently, only two of the original stations are operating: Gold Spring, Arizona, and Jornada, New Mexico. In addition to the meteorological data, there is repeat photography for the sites at a series of marked camera stations, which provides an indication of changes in vegetation cover over time.

Some preliminary results of the project are discussed in Breed and Reheis (1999), but most of the data have never been analyzed in a systematic fashion. An example of the application of this unique monitoring network to understanding variability of sand transport rates in relation to climatic parameters is documented in (Lancaster and Helm, 2000). The data on long-term variations in sand transport rates provide a record of the response of sand transport rates to external stressors, including drought periods and changes in the composition of vegetation communities over a period of two decades at Gold Spring and Jornada (Fig. 16). The Gold Spring data show the effects of heavy rainfall on vegetation cover and sand transport rates in the period 1992–1993 and subsequent droughts, while the Jornada data show an order of magnitude increase in sand flux since the mid 1990s, likely as a result of the change from a grassland to a mesquite-dominated landscape.

Dust Deposition in the Southwestern United States

This is a good example of a monitoring project that provides quantitative information on an important geologic process, as well as data that lead to a greater understanding of how the process responds to stressors. The project is ongoing and is designed to monitor dust deposition rates in areas of the Great Basin and Mojave deserts of the southwestern United States. Goals of the project are to determine the rate and composition of dust inputs to soils, and to relate dust accumulation to climatic patterns, especially the amount and seasonal distribution of rainfall, as it affects different dust source areas, including playas and alluvial areas. Results of the project are summarized in Reheis, (1997, 2003, 2006) and Reheis and Kihl (1995). The methodology used is briefly described above under Vital Sign 2, and discussed in detail in Reheis (1999, 2003).

Thirty-five dust trap sites in the eastern Mojave Desert and southern Great Basin have been monitored since 1984. Rates of deposition of silt and clay, clay, carbonate, and soluble salts have been determined on an annual or two-year basis, and compared to data on annual and seasonal precipitation at nearby weather stations (Fig. 17). Additional data on the chemical and mineral composition of the deposited dust were also generated.

The data show that generation and accumulation of dust is affected by the amount and seasonal distribution of rainfall. However, different source types (alluvium, dry playas, and wet playas) respond in different ways. A major factor in determining dust generation is the condition of surface sediments, especially their moisture content. For example, the flux of silt and clay and soluble salt increased following the El Niño events of 1987–1988 and 1997–1998 at sites close to playas with a shallow depth to groundwater. In this case, evaporative concentration of salts disrupted surface crusts and increased the susceptibility of surface sediment to wind erosion. The silt and clay flux increased during drought periods at sites downwind of alluvial sources and playas with deeper groundwater. This was the result of reduced vegetation cover on alluvial sediments, and local runoff events that

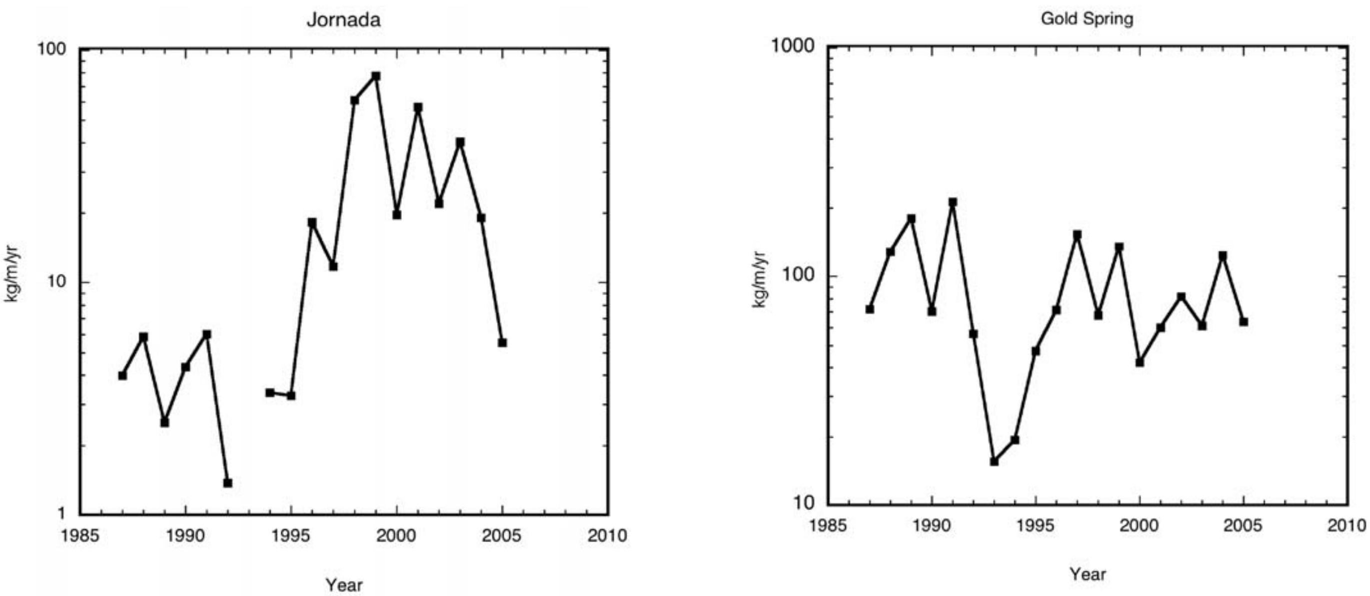

Figure 16. Changes in sand flux over time at Gold Spring and Jornada Desert Winds sites. Sand flux measured using Big Spring Number Eight traps.

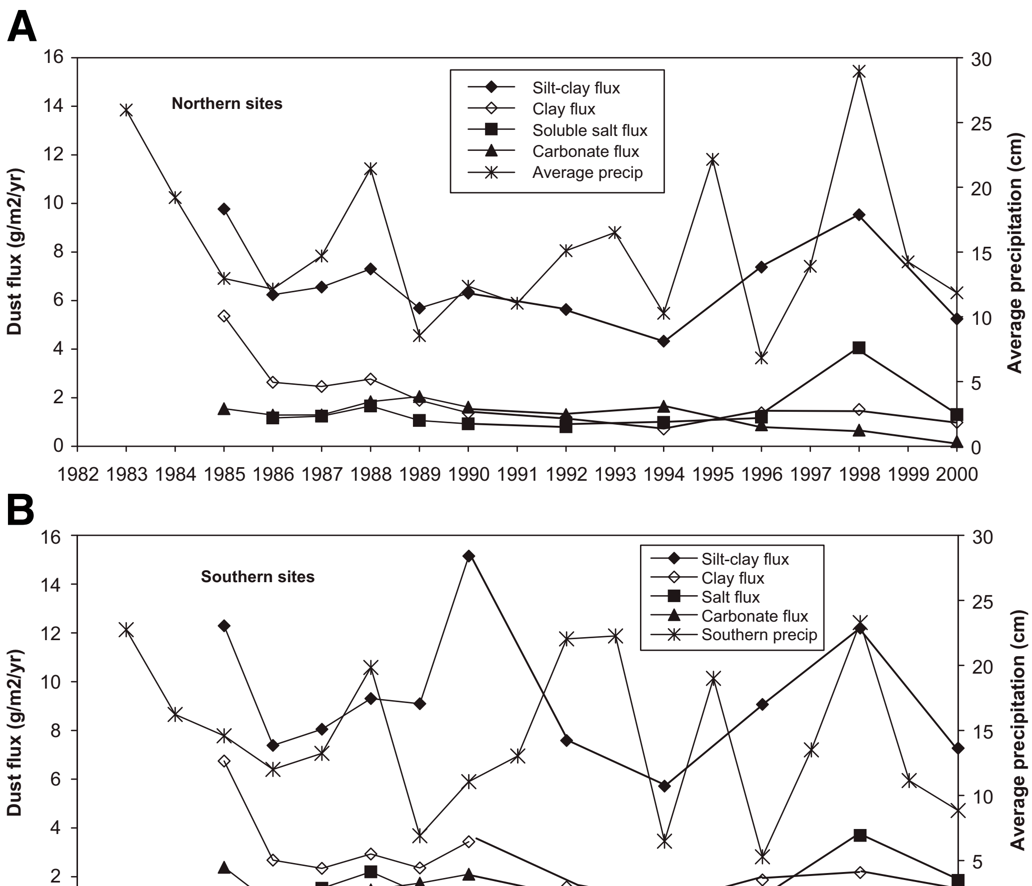

Figure 17. Changes in dust flux in the Mojave and Great Basin deserts (after Reheis, 2006). (A) Dust flux and precipitation at northern sites. (B) Dust flux and precipitation at southern sites.

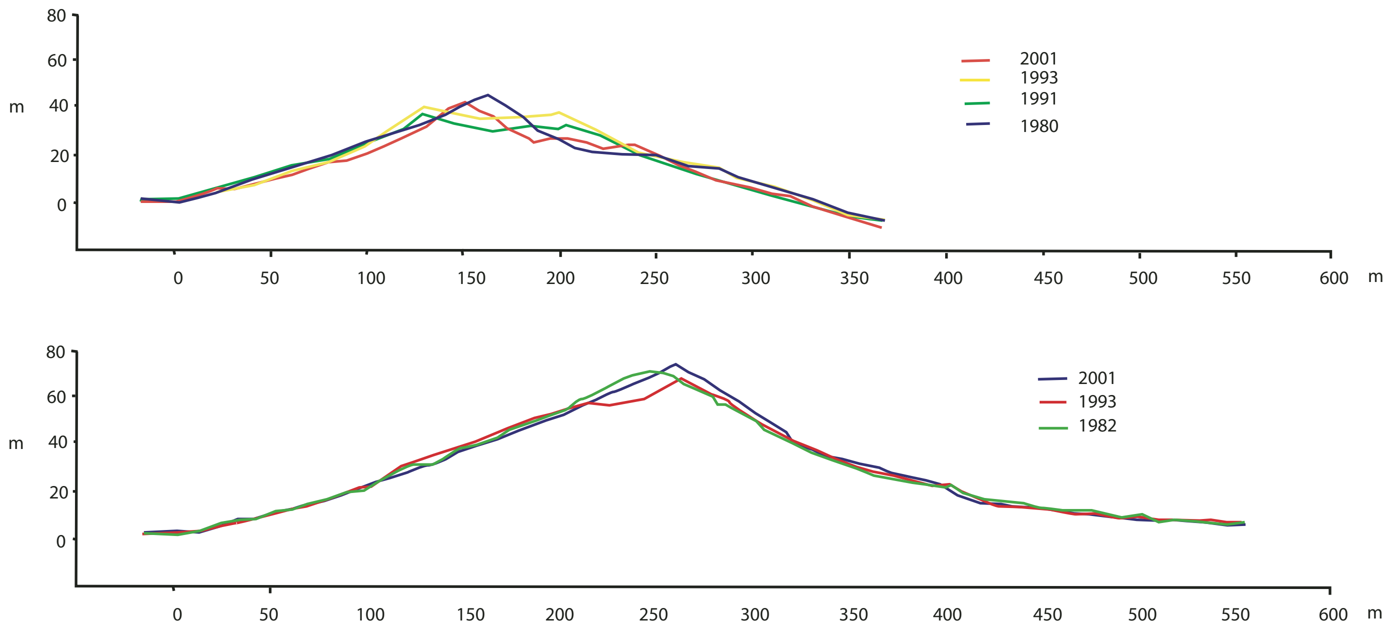

Figure 18. Changes in linear dune morphology (simplified from Livingstone, 2003).

delivered fresh sediment to playa margins and the distal portions of alluvial fans (Reheis, 2003, 2006). Reheis (2006) also noted geographical differences in the response of dust sources to precipitation variability, with a greater range of dust fluxes noted in southern (mostly Mojave Desert) sites.

Topographic Change on a Namibian Linear Dune

Most long-term studies of desert dunes have concentrated on monitoring rates of movement of small crescentic or barchan dunes via comparison of the position of dunes on aerial photographs taken at different time intervals. Studies of the dynamics of individual dunes are relatively rare. This project has monitored surface topographic change on a large linear dune in the central Namib Desert since 1980. Erosion pins were set up in 1980 and monitored weekly for the first four years (Livingstone, 1989). Subsequently, the dune was resurveyed in 1993, providing information on dune change over a decade (Livingstone, 1993), and again in 2001 (Livingstone, 2003). Methods used varied over the period of monitoring, from direct measurement of erosion pins in the intensive phase to use of a total station in 2001. Some of the erosion pins placed in 1980 survived to provide fixed points for subsequent surveys. Results of the intensive monitoring showed that the crest region of the dunes is the most active. The crestlines migrate over a lateral distance of as much as 14 m over a 12-month period, but with little net change over periods of years due to changes in seasonal wind directions. On the dune studied by Livingstone, the crest area changed from a relatively high single crest in the 1980s to a slightly lower double crest form in the 1990s, and then back to single crest form by 2001, regaining much of its original height (Fig. 18). The lower, or plinth, areas of the dune showed little change over the period of study. Livingstone (2003) attributed the changes in dune crest characteristics to changes in the relative magnitude and frequency of strong easterly winter winds, which increased in the late 1980s. The studies also suggested that these large dunes are not migrating because no lateral movement was detected. More recent studies show, however, that the rate of lateral migration of these dunes over periods of hundreds to thousands of years is only 0.13 m/year (Bristow et al., 2007), so the net migration over the period studied by Livingstone would have been ~0.25 m, and therefore difficult to detect.

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Manuscript Accepted by the Society 19 February 2009